Досліджено можливість вибору каналу регулювання ядерної енергоустановки з водо-водяним енергетичним реактором при маневруванні потужністю відповідно до добового графіка навантажень енергосистеми під час її експлуатації. Встановлено, що реакторна установка знаходиться у стійкому стані не тільки при нанесенні такого збурення, як зниження або збільшення потужності, але і при перемиканні програми регулювання

Ключові слова: ядерна енергоустановка, програма регулювання, потужність, стійкість реактора

Исследована возможность переключения программ регулирования ядерной энергоустановки с водо-водяным энергетическим реактором при маневрировании мощностью в соответствии с суточным графиком нагрузок энергосистемы во время её эксплуатации. Установлено, что реакторная установка находится в устойчивом состоянии не только при нанесении такого возмущения, как снижение или увеличение мощности, но и при переключении программы регулирования

Ключевые слова: ядерная энергоустановка, программа регулирования, мощность, устойчивость реактора

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RESEARCH ON MANOEUVRING CAPABILITIES OF A NUCLEAR POWER PLANT WHEN SWITCHING IN-USE CONTROL PROGRAMMES

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1. Introduction

Using a known control programme [1], manoeuvring capacity may be achieved, which brings the consumption schedule of electric power to conformity with the schedule of electric power generation [2]. However, it is impossible to reach full compliance due to an unexpected accident or an inclusion of new customers in an electric network. Therefore, an adaptation of existing power units to new specific working conditions becomes of current importance. It will allow not only nuclear power plants operation at the manoeuvring capacity but also even manoeuvring power control programmes of nuclear power plants (NPP) with the WWER-1000 in operation depending on the selected factors that influence the switching.

2. Analysis of previous studies and statement of the problem

In [3, 4], control programmes were analysed to identify advantages and disadvantages of each control programme. The main disadvantage was absence of studying control programme modes to explain why power declined with one control programme in use and why it increased while another programme was used. Systematized in [4], the control programmes' defects were attributed to the fact that during their creation special multi-level charts had not been developed. They could be used when working with models in large automation systems. All this would bring clarity to the concepts' presentation at the level of individual objects, states, and processes.

Energy release in the reactor core with manoeuvring power was examined in [5, 6]. Issues of structural optimization and how the heat flux changed at various control programmes were considered in [7, 8]. A regulator of boric acid to control the value of nuclear power capacity was offered in [9]. A new automated control power system that included the regulator of boric acid was examined in [10]. The development of new methods to control the NPP and to increase its safety was relevant and valid, but none of the suggested methods included the switching of power control programmes at the reactor unit being in operation. Study [11] described the development of a dynamic model for a thermal-hydraulic analysis of materials test reactors (MTRs) during a reactivity insertion accident. A static reactive compensator (SRC) was studied to analyse the effect on the problem of load flow of a power system [12]. In [13], the validity of the adopted scaling approach confirmed the fact about a very similar behaviour of the pressurized water reactor (PWR) and water-water energy reactor (WWER) types. Thermal-hydraulic analysis tasks aimed at supporting plant operation and control of nuclear power plants were undertaken in [14].

3. The purpose and objectives of the study

The purpose of the research is to develop object-oriented analysis (OOA) for the automated control system to enhance the capabilities of a manoeuvring unit with the WWER-1000 by switching the power control programmes of a NPP during its operation.

In accordance with the set purpose, the following research objectives have been identified:

– to develop an information model of an automatic power control system;

– to construct a state model of the nuclear reactor and the control system;

– to design technological algorithms of switching the existing power control programmes at the moment of reduced capacity.

4. Research material

4. 1. The development of an information model of the automatic power control system

An OOA theory has all of the aforementioned positive aspects, and it is advisable to apply it to the analysis of an automatic power control system of a NPP with the WWER-1000 in the suggested mode of operation.

According to [5], OOA is developed in three stages: an information model, a state model, and a process model. Abstraction of objects, their properties, and a set of relations in a single chart are located in the first stage. The next one presents a sequence of actions in states and events. This is the second stage of the OOA. Then, a transition diagram of these actions (double pole double throw (DPDT)) is developed at the third stage.

On the theoretical basis [5], a flow chart was built for the information model of an automatic power control system of the reactor plant with the WWER-1000. It is shown in Fig. 1.

From the point of view of analysing the subject area, the following objects were identified: the equipment of the first and second circuits, technical means of the low-level and upper-level control systems. Upon the recommendation [5], to complete the representation of the information model, its description was developed, which is summarized in Table 1.

The attributes marked in the information model were also summarized in Table 2 for description. The mathematical expressions presented below were taken from [2, 3].

As shown in Fig. 1, all objects of the information model are linked by three types of connection: for example, a "one-to-one relationship" between the control system and different types of regulators; a "one-to-many relationship" between the nuclear reactor, the steam plant, the pipe conduit of the first circuit, and the turbogenerator with regulators. At the same time, a "super type-to-subtype" connection identifies the base object regulator and copies of this object, as, for example, the regulator of the turbogenerator electric power and the regulator of rotary rotations per minute.

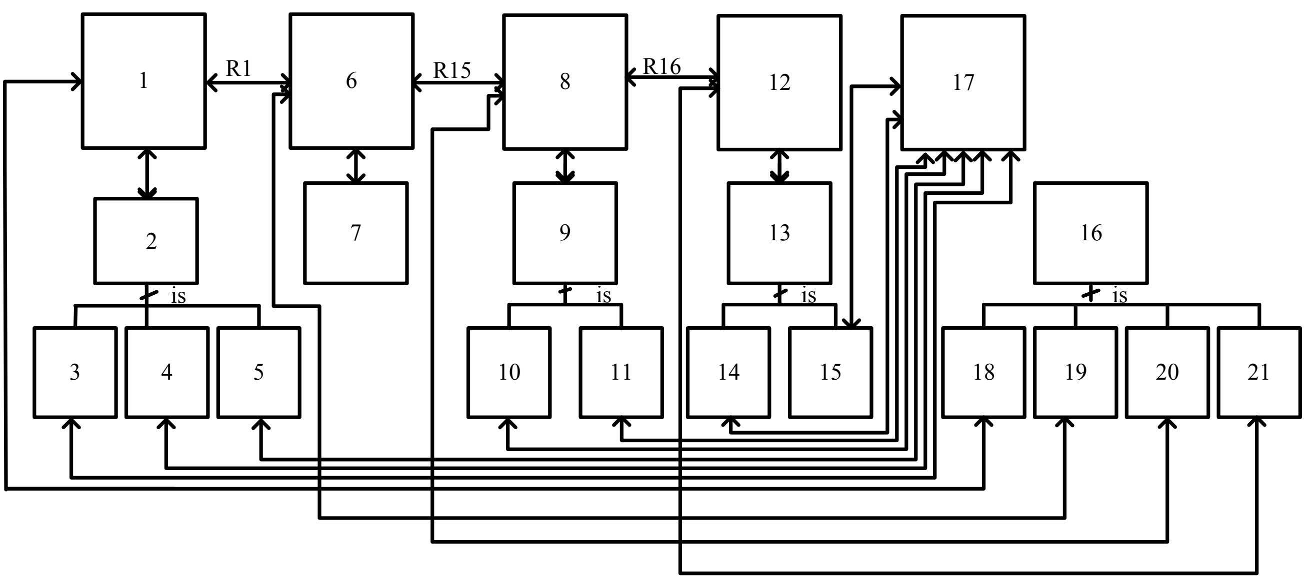

Fig. 1. A flow chart of the information model for an automatic power control system

Table 1

Description of the objects of the information model

№	Object's name	Description	Attributes
1	Nuclear reactor (NR)	Reactor type – WWER-1000; heat capacity – 3,000 MW	ID of the nuclear reactor; ID of the neutron power regulator (R2); ID of the average temperature regulator – the first circuit coolant (R3); ID of the axial offset (AO) regulator (R4); ID of the pipe conduit of the first circuit (R1); ID of the timer (R11); T_{in}, T_{out}, submerged length of control rods of the 10th group, neutron power, and an axial offset (AO)
2	Regulator	–	RC, TI, assignment; current value; control response
3	Neutron power regulator	It consists of an ionization chamber and an actuator – control rods	ID of the regulator (R2)
4	Regulator of the average temperature – the first circuit coolant	It consists of a measuring transducer, a setting mechanism, and an actuator – the main steam valve (MSV)	ID of the regulator (R3)
5	Regulator of the AO	It consists of a measuring transducer, a setting mechanism, and an actuator – control rods	ID of the regulator (R4)
6	The pipe conduit of the first circuit (PC1c)	The pipe conduit is 850 mm in diameter; the T_{out} of the nuclear reactor is 322 °C, and the T_{in} to the nuclear reactor is 289 °C.	ID of the pipe conduit of the first circuit (R1); ID of the boric acid regulator (R5); ID of the steam plant (R15); ID of the timer (R12); the concentration of boric acid; dead time
7	Boric acid regulator	It consists of a tank, boost pumps, and two valves transmitting boric acid and desalted water	ID of the boric acid regulator (R5); the current value; control response
8	Steam plant (SP)	The heat capacity is 750 MW; the evaporation is 1,470 t/h; the steam pressure is 64 atm; the steam temperature is 278.5 °C	ID of the steam plant (R15); ID of the regulator of the input temperature coolant in the nuclear reactor (R6); ID of the regulator of steam pressure in the SP (R7); ID of the turbogenerator (R16); ID of the timer (R13); steam flow consumption; pressure in the steam plant; the coolant temperature at the outlet of the steam plant
9	Regulator	–	RC, TI, assignment; current value; control response
10	Regulator of the input temperature coolant in the nuclear reactor	It consists of a measuring transducer, a setting mechanism, and an actuator – the MSV	ID of the regulator (R6)
11	Regulator of the steam pressure in the SP	It consists of a measuring transducer, a setting mechanism, and an actuator – the MSV	ID of the regulator (R7)
12	Turbogenerator (TG)	The active power is 1000 MW, the voltage is 24 kV; 1,500 rotary rotations per minute	ID of turbogenerator (R16); ID of regulator of turbogenerator electric power (R8); ID of regulator of rotary rotations per minute (R9); ID of timer (R14); rotary rotations per minute; electric power of turbogenerator
13	Regulator	–	RC, TI, assignment; current value; control response
14	Regulator of the turbogenerator electric power	It consists of a setting mechanism, a turbine control mechanism, a servomotor, and a control valve	ID of the regulator (R8)
15	Regulator of rotary rotations per minute	It consists of a measuring transducer, a setting mechanism, and an actuator – the MSV	ID of the regulator (R9)
16	Timer	It is used to create an event after a certain time	ID of the timer (R10); time left; event label; ID of the instance; time
17	Control system	Monitoring the work of complex objects, giving them normal operating conditions	ID of the control system
18	Nuclear Reactor timer	–	ID of the timer (R11)
19	The pipe conduit of the first circuit timer	–	ID of the timer (R12)
20	Steam plant timer	–	ID of the timer (R13)
21	Turbogenerator timer	–	ID of the timer (R14)

Table 2

Description of the information model attributes

Attribute's name	What affects it	Mathematical expression
T_{in} is the input coolant temperature in the nuclear reactor	the valve position	$t_{in}(\tau)=2\cdot(\frac{Q(\tau)+\frac{dt_S}{dP}\cdot P(\tau)}{k\cdot F_e})-t_{out}(\tau)$
T_{out} is the output coolant temperature from the nuclear reactor	the concentration of boric acid in the coolant	$t_{out}(\tau)=\left(\frac{\alpha\cdot F\cdot(t_{fuel}(\tau)-t_{av}(\tau))}{(Cp\cdot T\frac{dt_{av}}{d\tau})+(\frac{Cp\cdot T}{\tau_0})}\right)+t_{in}(\tau)$
h_{suz} is the submerged length of control rods of the 10-th group	AO	$\rho_{suz}(\tau)=a(\tau)\ \cdot(h_{suz}-h_0)$
C_{bor} is concentration of boric acid in the coolant	heating capacity	$\rho_{bor}(C_{bor})=\left(\int_0^{C_{bor}}\alpha_{bor}dC_{bor}\right)$
$G_s$is steam flow consumption		$D(\tau)=\frac{1}{r}\cdot\left[\begin{array}{l}Q\ (\tau)-G_s(\tau)\cdot(i'-i\ )-(V\ (\tau)\cdot\rho'\cdot\frac{di'}{dP}+\\+V(\tau)\cdot\rho''\cdot\frac{di''}{dP})\cdot\frac{dP}{d\tau}\end{array}\right]$
p is pressure in the steam plant		$P(\tau)=(-K_1\cdot G_s(\tau)+K_2\cdot t_{2E}(\tau)-K_3\cdot G_{fw}(\tau))-\left(T_P\cdot\frac{dP}{d\tau}\right)$
n is rotary rotations per minute	power frequency	$n=50$ Hz
N_{el} is electric power of the turbogenerator	steam flow consumption	$N_T(\tau)=\left(\frac{N}{G}\right)\cdot G_s(\tau),\ \ N_{TG}=0.95\cdot(N_T)$
AO is axial offset	submerged length of control rods of the 10-th group	$AO=\left(\frac{Q_t-Q_b}{Q_t+Q_b}\right)\cdot 100\,\%$
τ is dead time	the length of the main circulation pipeline	$\left(T_{TR1}\frac{dt_{SP}^{in}}{d\tau}\right)+t_{SP}^{in}(\tau)=t_{10}^{out}(\tau);$ $\left(T_{TR2}\frac{dt_1^{in}}{d\tau}\right)+t_1^{in}(\tau)=t_{SP}^{out}(\tau),$ $T_{TR1}=1.3\,\sec;\ \ T_{TR2}=3.3\,\sec$

4. 2. A state model construction of the nuclear reactor and the control system

In this study, only two states of the model are presented: the nuclear reactor (NR) model and the control system (CS) one. State models of other objects of the information model are not really interesting because they can only be in two states: on/off. Fig. 2 shows the state model of the nuclear reactor (NR).

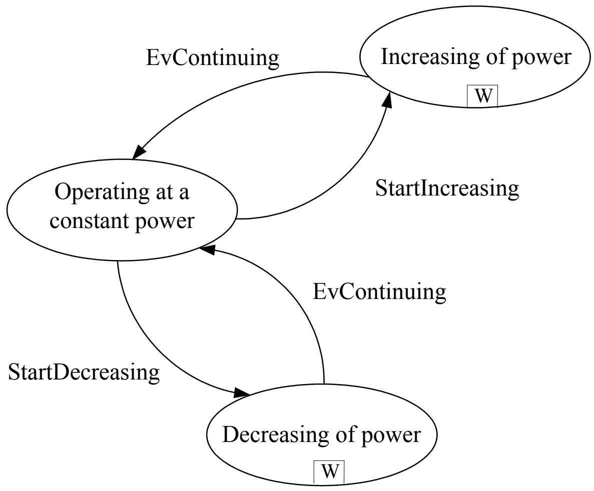

Fig. 2. A state model of the nuclear reactor (NR)

Table 3 below describes the events of the state model of the nuclear reactor (NR).

Table 3

List of events

Name of an event	Destination
StartIncreasing	Power starts to increase
StartDecreasing	Power starts to decrease
EvContinuing	Continuation of an event

Nowadays, in-use NPPs are operated under a control programme with a constant pressure in the second circuit, and the power manoeuvring is not carried out. In this regard, it has been proven [6] that still power changing of a NPP, with account for the schedule of daily pressure, can be performed, and it does not affect the value of important technological parameters.

Therefore, it is necessary to consider whether the important technological parameters are supported at a certain level: for example, if the nuclear reactor is unloaded from 100 % to 80 % of power by using one control programme, with 100 % of power reached by using another control programme.

State models of the nuclear reactor and the control system were considered in terms of an infinite cycle.

A state model of the control system is shown in Fig. 3.

It was assumed that the initial state of the NPP was “Operation at 100 % of power”. After 16 hours, the timer’s signal is activated, and the process of power reduction begins at a scheduled rate. If the transient is completed, the system moves to a new steady state of “Operation at 80 % of power”. If the process is not completed, calculation of the objective function determines the need to either switch the equipment or to continue the operation in the current configuration. In both cases, the system returns to the standby state of the completing the transition process, and the cycle is repeated. After switching the control programme and after 8 hours, the power increase of the nuclear power unit begins. A new state of “Operation at 100 % of power” begins after the completion of the process.

Below in Table 4, there is a description of the events from the state model of the control system (CS).

Table 4

List of events

Name of an event	Destination
EvTo100	Power increase to 100 %
EvTo80	Power reduction to 80 %
TimeOut	Time of transition is over
EvContinuing	Continuation of an event
EvEnd	Completion of an event
EvSelect1	Selection of the first control programme equipment
EvSelect2	Selection of the second control programme equipment
EvSelect3	Selection of the third control programme equipment

4. 3. Technological algorithms design of switching the existing power control programmes at the moment of reduced capacity

The third stage of the OOA implies a development of an action data flow diagram (ADFD), but in [7] the ADFD was replaced by a technological algorithm as a sequence of operations for a leap from one value of the technological parameter to another. In this study, using the proposal of [7], the following technological parameters were selected: the coolant temperature at the inlet and outlet of the reactor, the average temperature of the coolant, the pressure in the second circuit, and the quantitative measure of the reactor stability as the axial offset (AO). One of the problems when applying the disturbance to exploit the reactor is to maintain it in a stable condition [8, 9]. The change character of technological parameters while changing the power of the unit is determined by control programmes, so it is interesting to consider how the change of technological parameters in different control programmes affects the AO. Fig. 4 shows the characteristics of the NPP with the WWER-1000 in two control programmes.

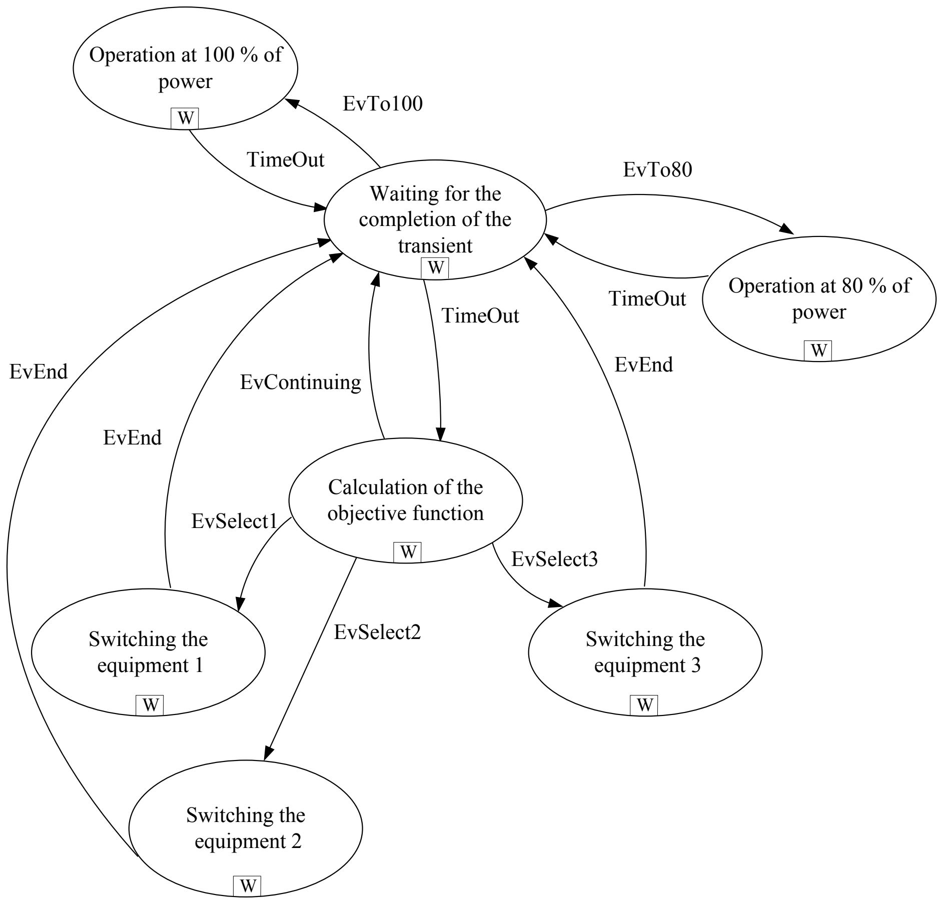

Fig. 3. A state model of the control system

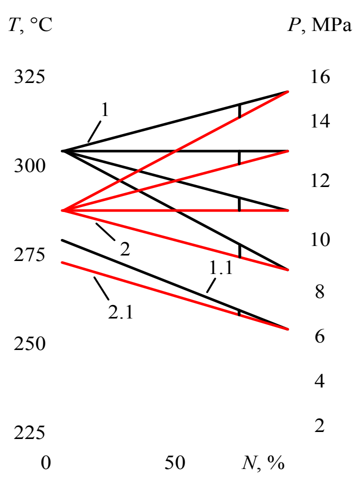

Fig. 4. Characteristics of the NPP with the WWER-1000:
1 is the point from which the reactor temperatures decline: the outlet, average, inlet and saturated steam temperatures,
1.1 is steam pressure in the second circuit while operating under the control programme at a constant average temperature;
2 is the point from which the reactor temperatures decline: the outlet, average, inlet and saturated steam temperatures,
2.1 is steam pressure in the second circuit while operating under the control programme at a constant temperature at the inlet of the rector

Fig. 4 shows the values of such parameters as temperature and pressure at different power levels. The dotted line indicates the transitions from one control programme to another while being switched. These transitions are the key moment of the research that will show if it possible to switch control programmes at 80 % of the reactor power.

5. Research results of switching control programmes at 80 % of power

An input coolant temperature in the nuclear reactor is calculated according to formula (1):

$$t_{in}(\tau) = 2\cdot\left(\frac{Q(\tau)\dfrac{dt_S}{dP}\cdot P(\tau)}{k\cdot F_e}\right) - t_{out}(\tau), \qquad (1)$$

where $Q(\tau)$ is the amount of heat transferred from the first circuit to the second, MW; $P(\tau)$ is the steam pressure in the second circuit, MPa; k is a heat transfer coefficient, W/(m^2·K); F_e is the total effective area of the heating surfaces in the steam plant, m^2.

The temperature of the coolant at the reactor outlet was calculated by (2):

$$t_{out}(\tau) = \left(\frac{\alpha\cdot F\cdot(t_{fuel}(\tau) - t_{av}(\tau))}{(Cp\cdot т\dfrac{dt_{av}}{d\tau}) + (\dfrac{Cp\cdot т}{\tau_0})}\right) + t_{in}(\tau), \qquad (2)$$

where Cp is the specific heat capacity of the coolant, J/kg·K; $\hat{o}_0$ is the coolant delay time, sec; m is the coolant mass in the reactor core, kg.

The average temperature of the coolant calculated by formula (3):

$$t_{av}(\tau)=\left(\frac{t_{out}(\tau)+t_{in}(\tau)}{2}\right). \quad (3)$$

The steam pressure in the second circuit was calculated as follows:

$$P(\tau)=\left(-K_1\cdot G_s(\tau)+K_2\cdot t_{2E}(\tau)-K_3\cdot G_{fw}(\tau)\right)-\left(T_P\cdot\frac{dP}{d\tau}\right), \quad (4)$$

where G_s is the steam flow rate, kg/s; G_{fw} is the feedwater flow, kg/sec.

The axial offset was calculated by formula (5):

$$AO=\left(\frac{Q_t-Q_b}{Q_t+Q_b}\right)\cdot 100\,\%, \quad (5)$$

where Q_t is energy release at the top of the core; Q_b is energy release at the bottom of the core [3].

Table 5 shows the solution of the equations (1 through 5) for the two control programmes at 100 % of power of the nuclear unit.

Table 5

Solution of the above-mentioned equations for the two control programmes at 100 % power of the nuclear unit

Name of the control programme	T_{in}, °C	T_{av}, °C	T_{out}, °C	P, MPa	AO
T_{av}=const	289	305.5	322	6.4	–3.41
T_{in}=const	270	296	322	6.4	–3.41

Using a mathematical model of the NPP with the WWER-1000 [3], realized on the basis of Matlab Simulink, simulation experiments on switching control programmes were carried out. In total, six switches were made, such as from T_{av}=const to T_{in}=const; from T_{in}=const to T_{av}=const; from T_{av}=const to P_2=const; from P_2=const to T_{av}=const; from T_{in}=const to P_2=const; from P_2=const to T_{av}=const. In short, the study presents the results of a single switching: from T_{av}=const to T_{in}=const. The simulation results confirmed the expectations. The experiment was conducted as follows: the power of the reactor unit was reduced to 80 % when working on the control programme at a constant average coolant temperature. An increase to 100 % of power was carried out under the control programme at a constant temperature of the coolant at the reactor inlet. Below are transient graphics. Below are transient graphics (Fig. 5–9).

For visualization, the simulation results are summarized in Table 6.

Table 6

Simulation results in numbers

Parameter	T_{in}, °C	T_{av}, °C	T_{out}, °C	P, MPa	AO
Time of transition, sec	$0.003\cdot10^4$	$0.025\cdot10^4$	$0.025\cdot10^4$	$0.0105\cdot10^4$	$0.024\cdot10^4$
Deviation value rel. units	2.6	2.9	3.7	0.35	0.01 %

From the data obtained as a result of simulation, it in obvious that the transient of selected values range from 30 sec to 4.16 min, the deviation is in the range of 0.35 to 3.7 rel. units, and the deviation of the AO values is 0.01 %. These figures are admissible in the procedural options while operating the nuclear power plant. According to Basic rules for operating nuclear power plants, a maximum deviation of the axial offset value is 2.59 %. The value of 2.59 % is the boundary; excess above this regulation is prohibited, and it leads to a forced stop of the reactor unit.

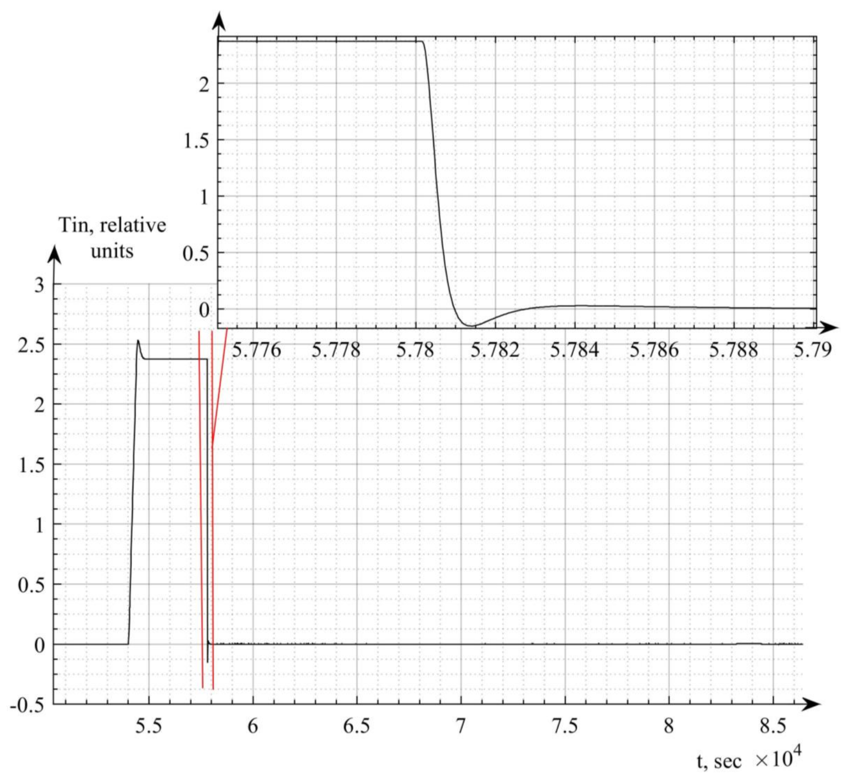

Fig. 5. A temperature curve at the reactor inlet where the switching point is highlighted by vertical lines and is shown in an enlarged view above

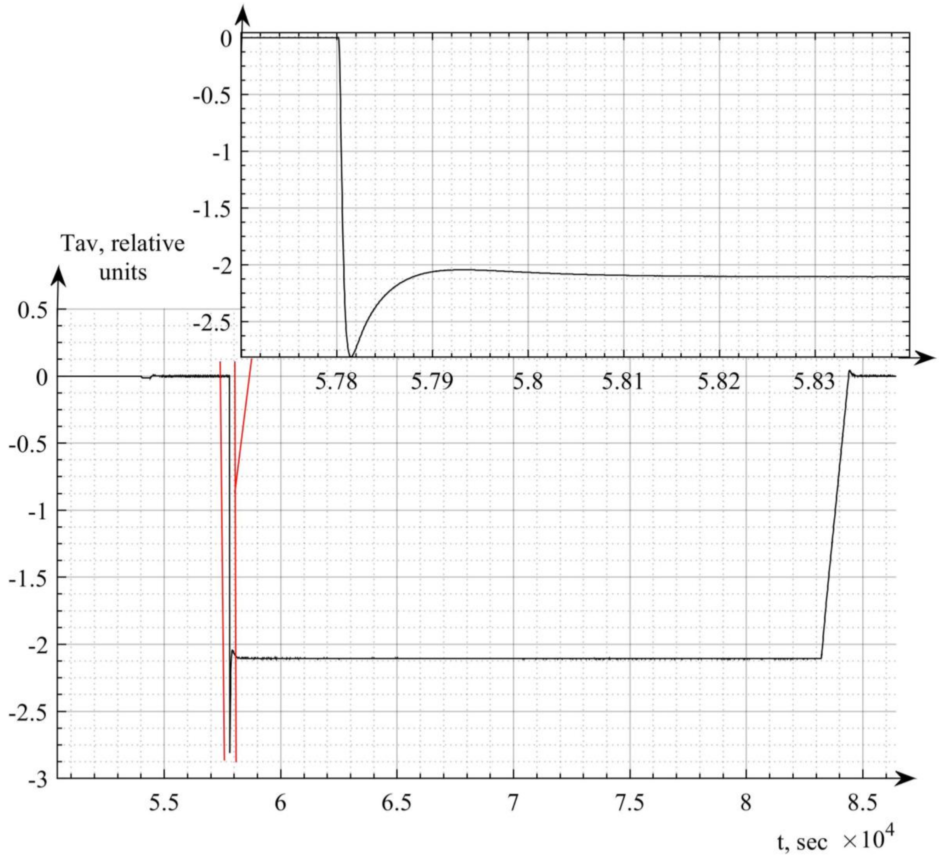

Fig. 6. An average temperature curve where the switching point is highlighted by vertical lines and is shown in an enlarged view above

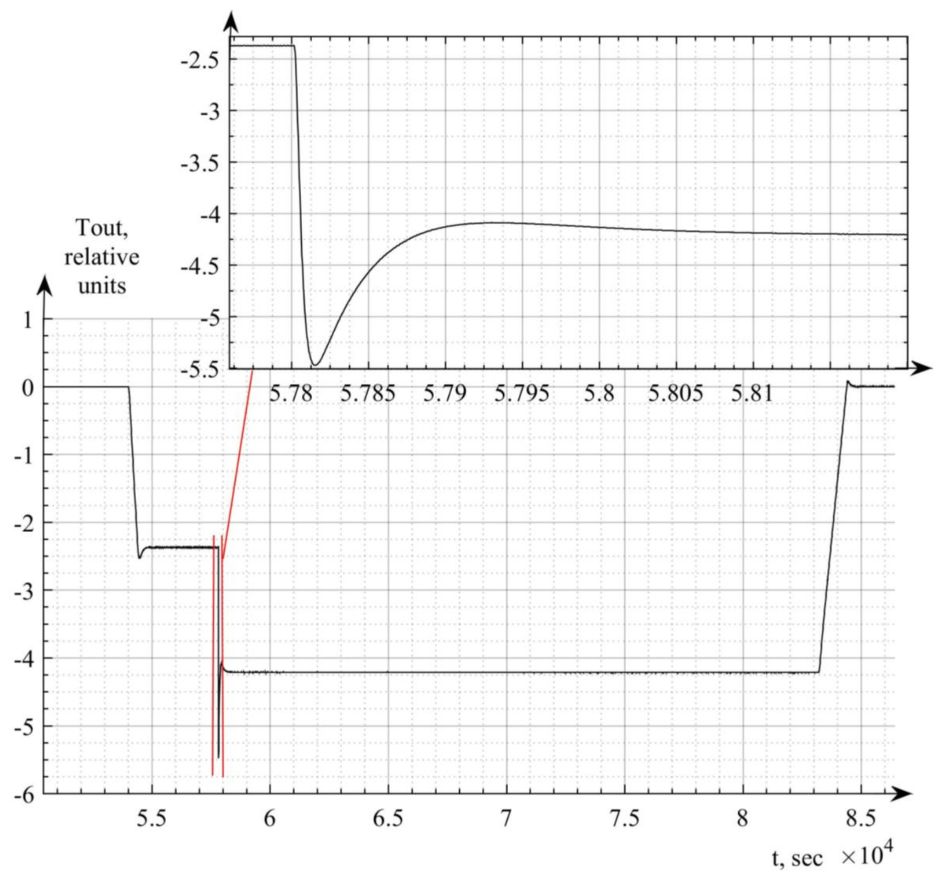

Fig. 7. A temperature curve at the reactor outlet where the switching point is highlighted by vertical lines and is shown in an enlarged view above

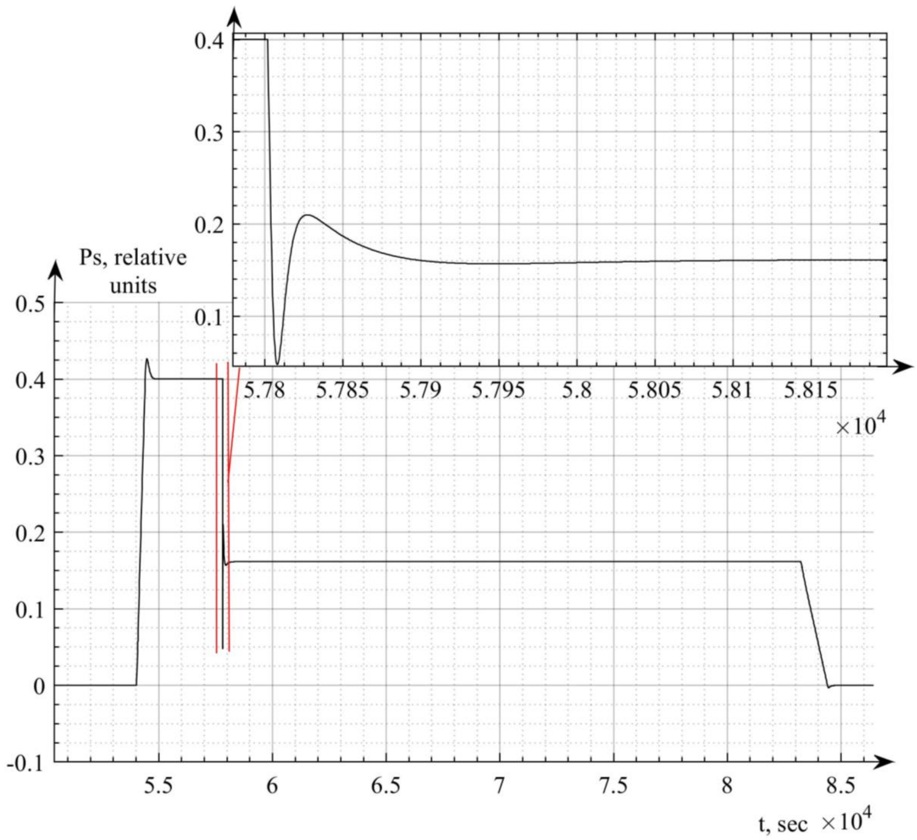

Fig. 8. A diagram of changes in pressure in the secondary circuit, where the switching point is highlighted by vertical lines and is shown in an enlarged view above

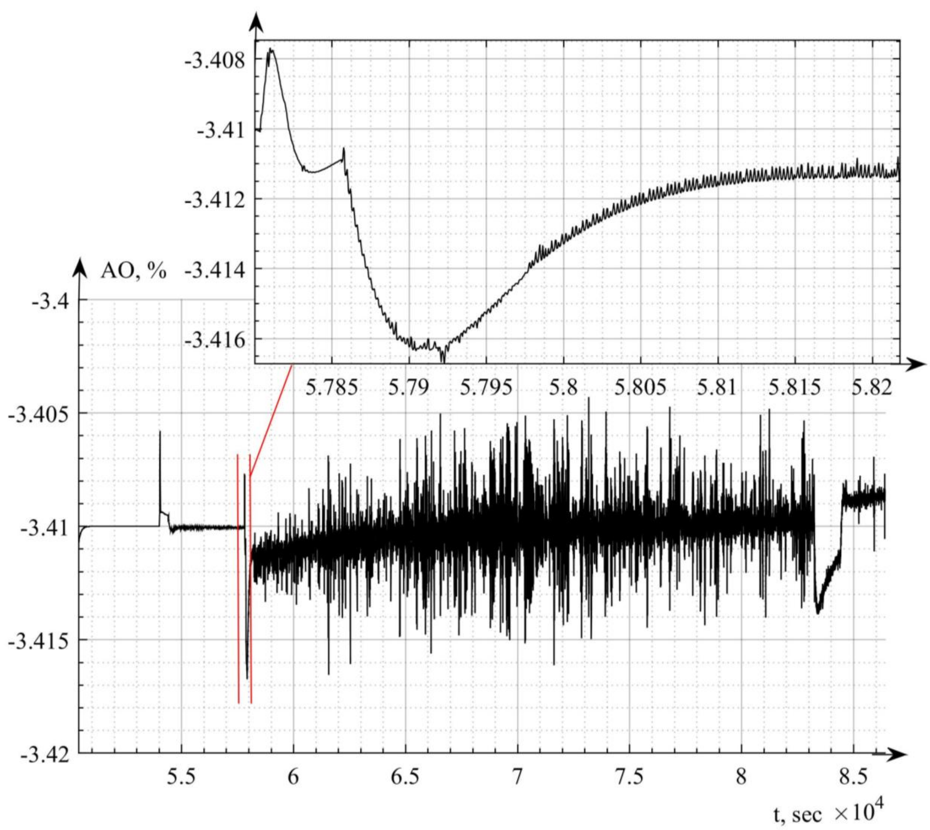

Fig. 9. A diagram of AO changes, where the switching point is highlighted by vertical lines and is shown in an enlarged view above

6. Discussion of the research results about the possibility of switching control programmes at nuclear power plants with the WWER-1000 of reduced capacity

This research is a continuation of a number of previous studies. In [9], a regulator of boric acid was suggested for controlling the reactor unit with the WWER-1000. The new power control programme with a constant inlet coolant temperature was invented in [10]. The present study is based on the principles of the aforementioned suggestions and innovations in the field of automation of power plants. Hence, the proposition of switching the existing power control programmes was successfully performed. It is for the first time that a minimum deviation of the AO was reached not in a stationary but in a transition mode of the power unit. It indicates a uniform energy release at the top and bottom of the reactor core as well as stability of the reactor unit while switching the existing power control programmes at a reduced output. Thus, the research has been quite beneficial, and its results can be applied at Ukrainian nuclear power plants with the WWER-1000.

7. Conclusion

1. A complex automatic power control system was developed by using three stages of OOA. This allowed switching power control programmes at Matlab Simulink. The equipment to operate one control programme was disconnected while the equipment responsible for the operation of another control programme was activated at 80 % of power, with minimum deviation values of technological parameters.

2. Moreover, according to the simulation results, control programmes during the operation of the nuclear power plant can be switched. The reactor unit remains in a stable state not only after applying such a disturbance as power reduction or increase but also after switching control programmes, which is evidenced by the values of the axial offset as a quantitative measure of the reactor stability.

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